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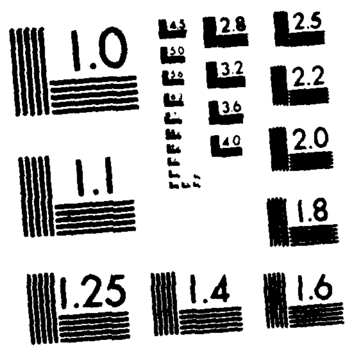

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LOCAL FREE SPACE MAPPING AND PATH GUIDANCE

William T. Gex and Nancy L. Campbell

Naval Ocean Systems Center
Autonomous Systems Branch (Code 442)
San Diego, CA 92152

ABSTRACT

This paper describes a method of mapping the local environment in front of a ground vehicle using acoustical sensors. The map outlines the extent of known freespace. This information is used to generate navigation points in the form of a subgoal and avoidance points which may be used by another process to dynamically generate a path. The map information is also used to intelligently steer the sensors to areas of the environment requiring further investigation. Inconsistencies in sensor returns are resolved with multiple sensor scans. While any inconsistencies are being resolved, the map, if in error, errs on the side of safety. These algorithms are being developed by the Naval Ocean Systems Center (NOSC) on the Ground Surveillance Robot project.

INTRODUCTION

Autonomous mobile robots require the ability to not only sense their environment, but to also navigate through it, avoiding obstacles and heading in the general direction of some goal. To this end, the more intelligent robot can accumulate the sensor data into a local map from which a path towards a goal can be determined. Therefore, mapping of the robot environment using sensory information has generated a great deal of interest.

There are currently two basic methods of storing information used in mapping an environment. One method represents the environment as a grid of squares, with square dimensions possibly ranging from 0.5 by 0.5 ft [1] to 3 by 3 meters [2]. The squares can be defined by discrete entities such as 'occupied', 'free space', or terrain type [3,4], or by graded values which represent probabilities of being occupied [5], or by both types of values [1]. The advantage of the grid method of map storage is its ease of generation and updating. Each square of the grid has some value which, as new information comes in, can be replaced or mathematically averaged. However, analysis of such a map for paths to a goal is difficult due to undefined object entities as a whole.

Another method of storing map information uses line segments to define object or free space entities [6,7,8,9,10]. These segments can even be generated from the grid-type map [2]. Associated with each segment may be one or both endpoints, type (object or free space), probability of type, or other mathematical functions useful in future analysis for path planning. The disadvantage of this method of map storage is the difficulty in updating the map. Is the segment generated from new sensor data a new segment or a repeat of an already existing segment in the map structure? If it is new, how should it be integrated with the existing segments? And if it is a repeat, how should the new information on this segment be integrated with the old information? The advantage, of course, of this method of mapping is that the obstacle and free space regions are defined such that path generation is more easily accomplished than with the grid storage method.

In the work examined by this paper, the line segment method of map representation is used. This eases the task of generating a subgoal and avoidance points used in navigating to a goal. By reducing the map to a subgoal and avoidance points, the amount of information passed to a path planner is dramatically decreased, allowing easier sensor data fusion. This line segment map representation distinguishes itself from other approaches in that it maps freespace and not obstacles. This paper describes the algorithm used to incorporate new sensor data with the existing collection of line segments. It

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also shows how this new map is used to generate a subgoal and appropriate avoidance points to be used by a path planner and to intelligently move sensors to scan relevant areas of the environment.

SYSTEM DESCRIPTION

The mobile robot used in this study is the Ground Surveillance Robot (GSR) as described in [11]. Briefly, this vehicle is an M114 Armored Personnel Carrier with sensor modules that include: vehicle attitude, satellite navigation, acoustical range finders, vision, and laser range finder. The vehicle objective is to traverse unknown terrain to a given goal while avoiding obstacles. The mapper described here uses data from the acoustical range finders, though the principles can be applied to other sensory information.

Figure 1 shows the GSR system architecture. It consists of independent modules, each communicating through an Intelligent Communications Interface (ICI) [12] across a shared local area communications network. The vision/laser range finder systems provide environment information at far ranges, leaving the near range (within 10 meters) to be covered by the acoustical sensors. A far range goal is generated by a Planning module. The acoustical sensor task is to map the immediate environment and generate a subgoal based on the mapped free space and the known location of the far range goal with respect to the vehicle. This subgoal is the desired position for the vehicle within this immediate environment. In addition, avoidance points are generated based on detected free space edges (obstacles). The subgoal and avoidance points are passed to a Locomotion module which controls the vehicle throttle, braking, and steering. The Locomotion module moves the vehicle through the environment away from avoidance points, towards the subgoal. Thus, an explicit path is not generated by the acoustical sensor module, but instead the path is generated dynamically by the Locomotion module from the subgoal and avoidance points.

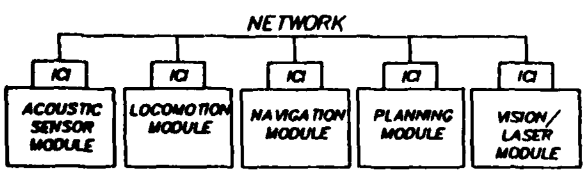

FIGURE 1: GSR SYSTEM ARCHITECTURE

Seven Polaroid acoustical sensors are mounted on the front of the vehicle as shown in figure 2. The three sensors mounted at the center of the vehicle are fixed in position, 15 degrees apart, resulting in a cumulative beam width of the three sensors (assuming an individual beam width of 15 degrees) of 45 degrees centered around the vehicle's dead ahead axis. The four steered sensors are mounted 2 on each side of the vehicle's front and can be steered to to any position between +/-75 degrees from dead ahead within 20 msec. These are "time of flight" sensors and measure the time for an acoustic wave to travel out to an object and reflect back. Based on this time and the speed of sound, a distance to the object is determined and is called the sensor's return. The maximum range of the sensors is 10 meters. Beyond this distance, any reflected acoustic wave is too weak to reliably sense.

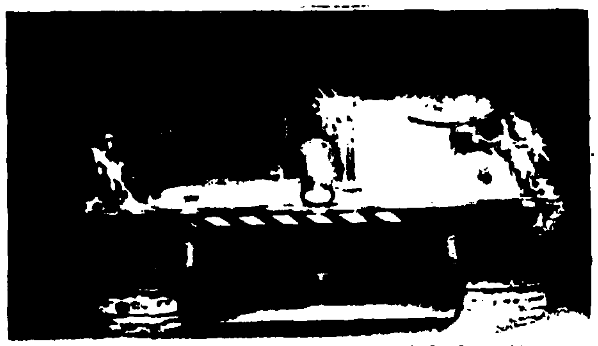

FIGURE 2: ACOUSTICAL SENSORS ON THE GROUND SURVEILLANCE ROBOT

MAPPING

The mapper creates a boundary of line segments that outlines the extent of known (by the acoustical sensors) free space. This boundary consists of an exterior boundary reaching out to the limit of the acoustical sensors (10 meters), and interior boundaries which represent areas that are either unmapped or show an object, and which are completely surrounded by identified free space. There is a separate structure for each interior boundary and one for the exterior boundary. Each line segment stored in these structures contains

(1) the x,y location of the segments' right-most (as seen from the vehicle) endpoint in absolute coordinates,

(2) the sighting (e.g. free space or object),

(3) the slope and y-intercept of the segment with respect to the absolute coordinate frame, and

(4) the direction the line segment should be traversed to keep known freespace on the left-hand side.

The mapper takes range information from the sensor and creates a triangle to represent the acoustical cone dispersion in two dimensions, with the sensor location as one vertex. (The error associated with this approximation of the arc by a straight line is less than one percent.) The interior of the triangle is known to be free space. The edge opposite the sensor vertex has the only legitimate sighting which can be either 'object' if a sensor return of less than 10 meters is measured, or 'free space' if the sensor return is greater than 10 meters (i.e., the sensor timed out without detecting anything). If the sighting is object, then an object exists somewhere along that segment. It is unknown exactly where the object is located due to the dispersion of the audio signal, so the entire area of the segment and beyond is considered object until future returns crop it with free space sightings. The edges of the triangle adjacent to the sensor position are called 'radial' segments to indicate that they have no legitimate sighting (free space or object) associated with them.

The union of the free space inside the sensor triangle (new data) with the existing free space boundary creates the updated free space boundary. To determine the triangle of the new sensor data, the vertices of the triangle are first determined in absolute coordinates using vehicle position and heading, and sensor position, heading and return. Then the triangle segments' slopes and y-intercepts with respect to an absolute origin are calculated.

All intersection points between each triangle segment and existing boundary segments are then determined using the slope/y-intercept representation of each segment. Each intersection point is stored in a structure that contains

(1) the absolute x,y position of the intersection,

(2) the intersecting segment of the boundary,

(3) the intersecting leg of the triangle,

(4) the order of its occurence on the boundary (from right to left on the exterior boundary and clockwise on the interior boundary), and

(5) the order of its occurence on the triangle (counterclockwise begining at the sensor vertex).

The new exterior boundary is formed by tracing the existing boundary from right to left. (An example of this tracing is explained in the next paragraph and shown in figure 3.) This keeps the known free space region always on the left hand side of the traced boundary. (The choice of right to left is arbitrary and could be done left to right with free space located on the right hand side.) When an intersection point is encountered while tracing the existing boundary, the new boundary follows the right-most segment (either old boundary segment or new triangle segment) to the next intersection point, where the process repeats. Tracing of the new boundary continues following the right-most path until the last point in the old exterior boundary structure is reached. The right-most path is used in order to expand the known free space boundary into unknown territory as much as possible. This process will create new boundary segments and delete old ones, though the majority of old boundary segments will remain unchanged since the union of new sensor data with existing boundary usually creates small additional freespace. As segments fall behind the vehicle due to its forward movement, they are deleted from the map.

Figure 3 shows this procedure. Two intersection points (P and Q) are found in the union of the old exterior boundary with the new sensor data. Intersection point P is associated with segment 6 (6-7) of the old boundary, and segment A (AB) of the new sensor data, while intersection point Q is associated with segment 6 of the old boundary, and segment C (CA) of the sensor data. The new boundary is formed by tracing the old boundary from point 0 through point 6 and up to the intersection point P. The right-most segment at intersection point P is the top portion of triangle segment A (PB). Therefore from intersection point P, the new boundary is traced along the top portion of segment A. Triangle segments B (BC) and C (CQ) are then followed until intersection point Q is encountered, at which time a new decision is made. Since the remainder of segment 6 (Q7) is more right than the remainder of segment C (QC), the remainder of segment 6 is chosen as the next segment on the new boundary. Since there are no more intersections, the new boundary continues following the old boundary segments until the end point, point 14, is reached.

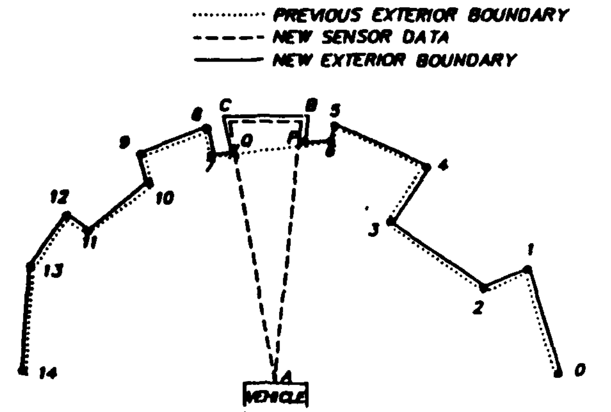

FIGURE 3: UPDATING EXTERIOR BOUNDARY

During this process of determining the new boundary, the next intersection point on the exterior boundary is checked to see if it is also the next intersection point on the triangle. In figure 4, the new boundary follows segment PB from intersection point P. However, the next intersection point on the existing exterior boundary (Q) is not the same as the next intersection point on the triangle (S). When this occurs, a new interior boundary is created, and the segments are traced clockwise until a triangle segment can close it up. In figure 4, the interior boundary traces segments QE and ER before finding segment RQ to close it. The next intersection point on the exterior boundary (S) is then checked to see if it is the next intersection point on the triangle before the interior boundary was formed (S). Since it is in this example, the new exterior boundary continues from the last intersection point P and traces segments PB, BC, and CS before tracing the remainder of the existing exterior boundary.

The existing interior boundaries are examined for intersections with the new sensor data. If intersections occur, the interior boundary can be updated. In figure 4, interior boundary I is intersected twice. It is traced clockwise, beginning at point I-0, until intersection point T is encountered. Again, the right-most path is chosen to cut into unknown space as much as possible and segment TU becomes the second segment of the interior boundary I. The process continues until the beginning point of the interior boundary is reached. (Segments U,I-2 and I-2,I-0 become the third and fourth segments respectively.) During this process, additional interior boundaries may also be created (eg. an interior boundary may be split into two interior boundaries).

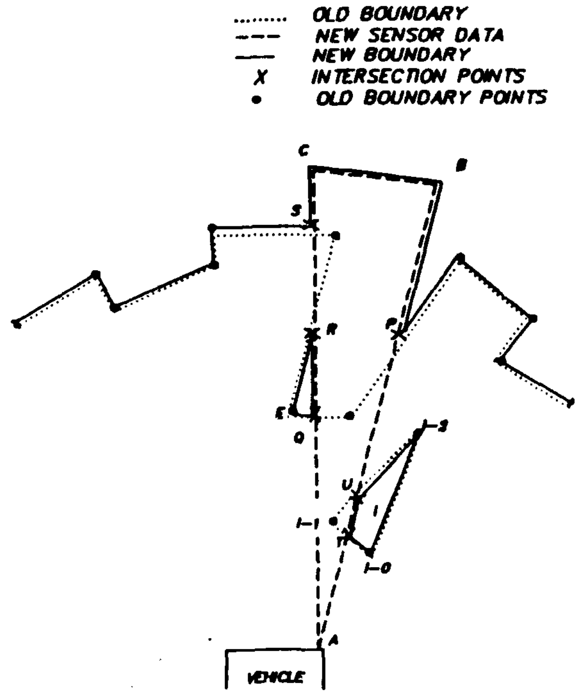

FIGURE 4: CREATING AND UPDATING INTERIOR BOUNDARIES

Each interior boundary is also checked to see if the new sensor data eliminates the interior space (i.e., there are no intersections and the entire interior boundary falls inside the triangle). If so, that interior boundary structure is deleted.

Sensor Unreliability

The acoustic sensors occasionally report false positive returns (an object is detected that doesn't exist) and false negative returns (an existing object was not detected). Others [1,5,6,9] have handled this sensor unreliability by associating with each point or segment in the map some probability that the data is correct. Consistent sightings in one area will increase the probability that the sighting is correct, while intermittent sightings will reduce the probability. Analysis of the map for paths to a goal then must consider these probabilities by picking the path that has the most likelihood of being traversible.

In this work, the approach taken to the sensor unreliability problem is to report a map which if in error, errs on the side of safety, while resolving any potentially dangerous inconsistencies by multiple sensor scans. Therefore, while the map may be temporarily in error, the complexity of analyzing a map containing "fuzzy" segments is avoided.

For example, if the new sensor data reports an object that is inside an area that was previously mapped as free space, one of three explanations is valid:

(1) previous free space reporting was erroneous (false negatives),

(2) the new object report is erroneous (false positive), or

(3) the environment is dynamic (moving objects).

The most dangerous response to such an inconsistency is to ignore the new object report. Therefore, the new boundary map incorporates this new object segment by projecting the triangle's radial segments beyond the object segment until they intersect the existing boundary segments (see figure 5). The new boundary traces these projected radial segments and the object segment between the intersection points. Otherwise the boundary remains the same. If the new data report is in fact a false positive, the only penalty is that a path may be planned around an object that doesn't exist. Future returns from that area should indicate free space, and the false positive will eventually be erased, perhaps before the vehicle takes unnecessary detours.

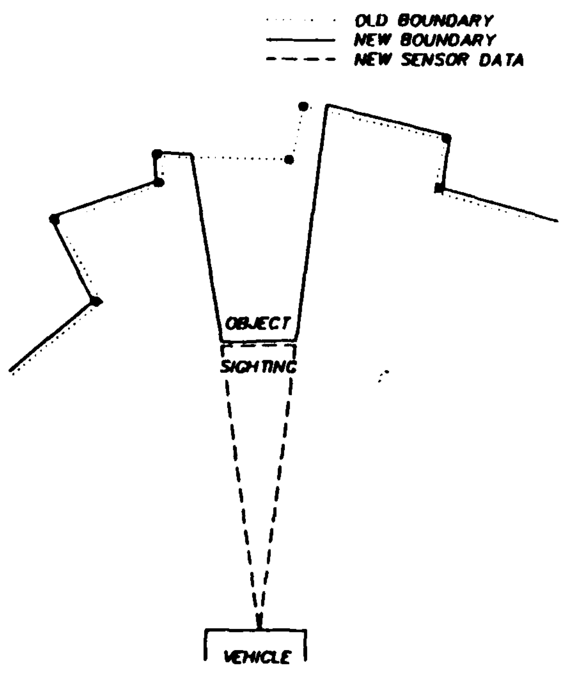

FIGURE 5: INCLUDING AN OBJECT SIGHTING

If the new sensor data completely erases a pre-existing object segment, again, three explanations are possible:

(1) previous object sighting was erroneous (false positive),

(2) the free space reporting is erroneous (false negative), or

(3) the environment is dynamic.

In this case, the most dangerous response is to ignore the previous object sighting. Therefore, the object is not ignored in subgoal and avoidance point determination until four different sensors (if possible) have checked the area in question. This is accomplished by preventing the passage of subgoal and avoidance point positions to the Locomotion module until the four new sensor returns are analyzed. The mapper does erase the object segment in question from the map, while directing four sensors to the area. Each return that comes in is then integrated into the map as usual. If the object did exist and was erroneously erased, it will be returned and incorporated into the map as described above. After the four returns have been analyzed, new subgoal and avoidance point positions are calculated from a presumably correct map and are allowed to pass to the Locomotion module. If while resolving one conflict, another conflict arises, the Locomotion module is told to stop until all conflicts are resolved.

SUBGOAL AND AVOIDANCE POINT GENERATION

After the new map is generated, the subgoal is determined. The subgoal will always be located within (or on the edge of) the space mapped by the sensors. The choice of subgoal is dependent on the contents of the immediate environment and the location of the goal. A hierarchy of possible choices exists, from the most direct route to the goal, to more roundabout routes when the direct route is unavailable.

The first choice for a subgoal (SG) is directly along the line (VG) between the vehicle center and the goal (G) (see figure 6). The intersection of this line with the exterior boundary is found. If the intersection is with a free space or a radial segment, then the intersection point is saved as a possible SG. The segments around the intersection point are examined to determine if the opening through the boundary is wide enough to accommodate the vehicle (i.e., there are no nearby object segments). If the

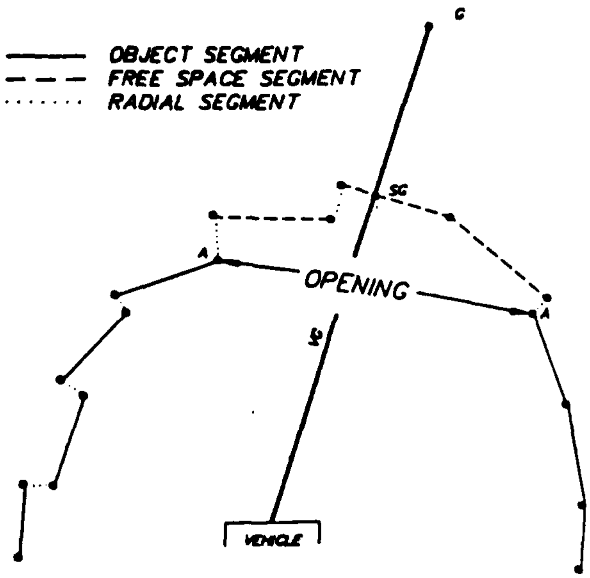

FIGURE 6: DIRECT PATH TO GOAL

opening is wide enough, the intersection point becomes SG.

If this opening in the exterior boundary is not wide enough, or the intersection is with an object segment, the next choice for SG is on a free space section of exterior boundary on either side of VG (see figure 7). Free space sectors (contiguous free space and radial segments) are first examined to see if their width is wide enough for the vehicle to pass. The free space sector with such an opening that is closest to VG is chosen to be the subgoal sector. If no free space sector is wide enough, the subgoal sector is the widest free space sector within a certain angle (currently +/-30 degrees) of VG. If no free space boundaries exist within this angle window, then the free space boundary outside of this window closest to VG is chosen as the subgoal sector.

Given a subgoal sector from free space boundaries, a point is selected along the line connecting the start and end points of the sector. This point bisects the line if the opening is less than the vehicle safety width (the width of the vehicle plus a safety margin, currently about one-third of the vehicle width). If the opening is greater than the vehicle safety width, the point is chosen at 1/2 of the vehicle safety width from the endpoint closest to VG. A line is then drawn between this point and the vehicle center. SG becomes the intersection of this line with the exterior boundary. Figure 7 exemplifies the determination of SG when the map contains one free space sector that is not in the direct path (VG) between vehicle and G. SE represents the line between the start and end points of the free space sector. Point X represents the intersection point a distance (d) of 1/2 of the safety width from the endpoint (E) closest to VG.

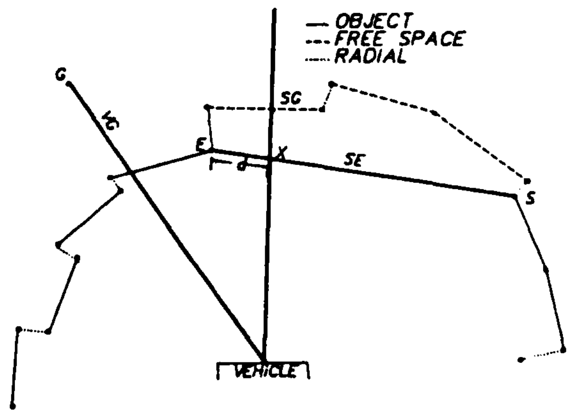

FIGURE 7: INDIRECT PATH TO GOAL THROUGH FREE SPACE SECTOR

If there are no free space boundaries in the current map, the next choice for SG location is in a long radial segment since radials represent unexplored territory that might be free space. (Long radials are radial segments or series of contiguous radial segments that are at least as wide as the vehicle safety width.) The largest long radial is chosen for SG location. Long radials outside an angle window (currently +/- 30 degrees) are handicapped by the angular distance between VG and the line between the vehicle center and the closest radial endpoint. A point is found which bisects the chosen radial segment. A line is then drawn between this point and the vehicle center, and SG becomes the intersection of this line with the exterior boundary. Figure 8 shows a map with no free space and only one contiguous radial segment large enough to accommodate the vehicle. The point X marks the bisection of the opening of the radial space.

If there are neither free space boundaries, nor long radial segments, SG is chosen as the endpoint of an object segment that is farthest from the vehicle; the hope being that as the vehicle continues to move forward, an opening is detected by the sensors. Distances between the vehicle and the object segment endpoint are handicapped when the object lies outside the angle window as described previously. This situation is depicted in figure 9.

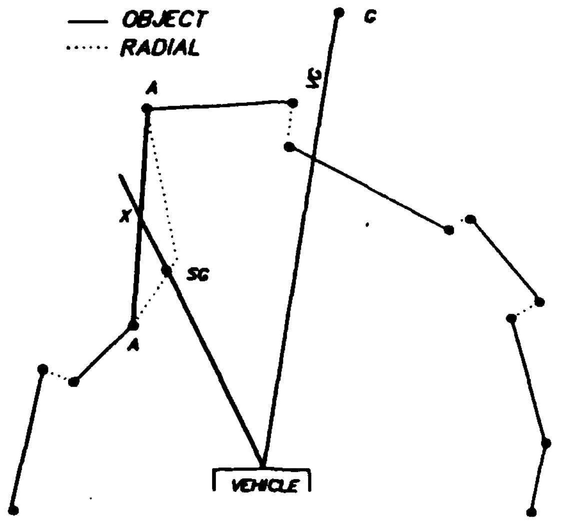

FIGURE 8: INDIRECT PATH TO GOAL THROUGH RADIAL SEGMENTS

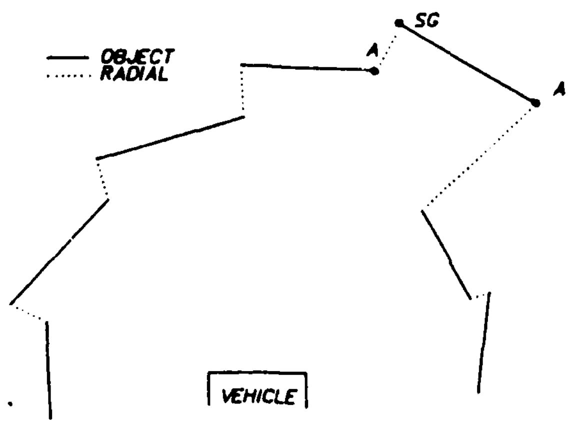

FIGURE 9: VEHICLE SURROUNDED BY OBJECTS

Once SG is found, new avoidance points (A) are selected as:

(1) the endpoints of the opening along the direct route (see figure 6),

(2) the endpoints of the subgoal free space sector (points S and E in figure 7),

(3) the endpoints of the long radial segment (see figure 8), or

(4) points on either side of the farthest object point (see figure 9).

Each interior boundary also has associated with it an avoidance point selected as the point closest to the path to SG. Old avoidance points (from previous subgoals) are repositioned or removed as the map is updated.

INTELLIGENT SENSOR MOVES

Map information, along with subgoal and avoidance point determination, are used to guide movement of the steered sensors to areas of the environment that require further investigation. Several types of moves are currently utilized. The two inside steered sensors are periodically moved to scan the area immediately adjacent to the -22.5 degrees to +22.5 degrees field of view of the fixed sensors, to cover blind spots in front of the vehicle. Steered sensors are also directed to scan interior boundary avoidance points to further delineate the interior object. The sensors will examine the direct path between the vehicle and the goal to determine if a more direct route is possible. They will also periodically search long radials which represent unmapped regions. And finally, the steered sensors are asked to verify potentially false negative and false positive reports, as described earlier.

FUTURE WORK

The determination of subgoal and avoidance points in this work doesn't currently consider the possiblity that the vehicle may not be able to get to the designated subgoal. For example, interior objects or a convoluted exterior boundary may be in the path between the vehicle and the subgoal. Or the opening between interior objects or convoluted exterior boundary may be too narrow to allow vehicle passage to the subgoal beyond. The designation of avoidance points should guide the Locomotion module in selecting a passable route, but a better approach would be to verify that the selected subgoal is reachable. If the subgoal is not reachable, a closer subgoal should be selected that is reachable. This can be accomplished by reiteratively checking the direct path between the vehicle and the proposed subgoal for non-free space within the swept width of the vehicle. If non-free space exists within this area, another subgoal should be selected. The final subgoal which is reported to the Locomotion module then is guaranteed to be reachable in a direct manner. Only the turning radius of the vehicle is not considered in subgoal selection, though this too can be added into the check on reachable subgoal.

CONCLUSION

The GSR Acoustical Sensor Module implements the following behavior which is needed to traverse unknown terrain in real time:

- "Sharpens the picture" of local terrain with each sensor fire

- Steers its sensors to probe areas of interest

- Reduces large amounts of information in the map to a few points for navigation purposes

The GSR Acoustic Sensor Module hardware and software has been implemented and works well in a static environment. This module is currently being integrated with the GSR Locomotion Module and they will be tested in a moving vehicle on local terrain.

ACKNOWLEDGMENTS

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